

TROPOSPHERE (FIRST) FOR SOFIA

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ABSTRACT

We describe the Far-Infrared Spectroscopy of the Troposphere (FIRST) experiment presently under development by NASA Langley. FIRST is a Michelson interferometer covering the spectral range from 10 to 100 μm in wavelength (100 to 1000 cm^{-1}) at 0.625 cm^{-1} (unapodized) spectral resolution. The far-infrared (far-IR, 15-100 μm) remains essentially unobserved directly despite containing up to 50% of the planet's outgoing longwave radiation and being a major factor in the planet's greenhouse effect. FIRST is developing the technology required to enable routine measurements of the far-IR from space, airborne, or balloon platforms. The FIRST project is funded by the Instrument Incubator Program (IIP) of the NASA Earth Science Technology Office (ESTO). The instrument will be demonstrated during a high altitude balloon flight in Spring, 2005. FIRST on SOFIA offers unique opportunities to investigate water vapor spectroscopy, cirrus radiative properties, the Earth's greenhouse effect, and water vapor feedback.

FIRST BACKGROUND

The radiation budget of the Earth system was the first quantitative measurement to be made from orbiting satellites, as proposed by Suomi (1957). Since that time, radiation budget measurements have consisted of the total (reflected solar plus emitted thermal infrared) radiation and the reflected solar radiation; these are spectrally integrated or broadband measurements with little spectral discrimination. The emitted longwave radiation is obtained by subtraction of the two classic energy flows. These measurements provide the integral constraints on the Earth's climate and energy budget. The response of and feedbacks within the Earth's climate system are determined by the terms of the integral, i.e., the absorption and emission spectra. Since the first measurements of Suomi, radiation budget measurements have been refined significantly in terms of their spatial resolution, angular sampling capability, and radiometric calibration (Wielicki et al., 1996). Despite the continuous improvement, radiation sensors are still making the same basic measurements as 40 years ago with little additional spectral distinction.

Remote sensing of the Earth's energy balance is an eight dimensional sampling problem (Wielicki et al., 1996). The improvements over the years in spatial, angular, and temporal (Harries and Crommelynck, 1999) sampling address seven of the eight dimensions. The remaining critical dimension, the spectral dependence of the radiation balance, and the far-IR in particular, have yet to be comprehensively observed. The Far-Infrared Spectroscopy of the Troposphere (FIRST) program

represents NASA's investment in the technology required to measure the Earth's emission spectrum in order to achieve a significant advance in climate and atmospheric remote sensing.

RELEVANCE OF THE FAR-INFRARED

The scientific case for measuring the far-infrared emission directly is reviewed by Mlynchak *et al.* (2002) and references therein. We define the far-IR to encompass wavelengths between 15 and 100 μm because this portion of the Earth's emission spectrum is not directly observed from space despite its fundamental importance. Earth's climate is influenced strongly by radiative cooling associated with emission of infrared radiation by water vapor at far-IR wavelengths extending out beyond 60 μm . The free troposphere cools radiatively almost exclusively in the far-IR. Water vapor is also the principal greenhouse gas, absorbing a significant fraction of the upwelling radiation and providing much of the downwelling longwave flux that warms the Earth's surface (i.e., the greenhouse effect). The distribution of water vapor and associated far-IR radiative forcings and feedbacks are well recognized as major uncertainties in predicting future climate.

We also note that the outgoing far-infrared radiation is modulated by cirrus clouds [9]. The prevalence and persistence of cirrus cloud systems, especially in the tropical upper atmosphere, implies that cirrus clouds play an important role in climate (Liou, 1986). The effects of cirrus in attenuating the far-IR to 25 μm have been shown by the Russian *Meteor* spacecraft (Spankuch and Dohler, 1985). Spectral measurements of the far-IR may also offer the potential for increased accuracy in water vapor profiles retrieved from emission measurements (Mertens *et al.* 2002). Measurements of the far-IR will contribute significantly to understanding how the Earth is responding to various natural and anthropogenic forcings. Cirrus optical properties may also be derived from measurements of the far-IR (Yang *et al.*, 2003).

FIRST SENSOR TECHNOLOGY

The design goals of the FIRST instrument are as follows:

- Spectral coverage: 10 - 100 μm
- Spectral resolution: 0.6 cm^{-1}
- Nadir viewing IFOV, 10 km spatial footprint (for a space-based instrument)
- NE Δ T: 0.2 K 10 to 100 μm (goal); 0.2 K 10 to 60 μm , 0.5 K 60 to 100 μm (requirement)
- Daily global coverage for a space-based instrument

The spectral coverage and spectral resolution are driven by the need to measure the unobserved far-IR together with the CO₂ 15 μm band for simultaneous temperature retrievals and validation against existing mid-IR sensors. The IFOV is driven by the need to be able to isolate clear and cloudy fields of view. The daily global coverage capability, which impacts primarily the detector focal plane array, is to ensure global observations of water vapor and that as much as possible of the natural spatial variability in the radiation and cloud fields is observed. The temperature sensitivity of 0.2 K is required for temperature profiling and to detect the climate change fingerprint.

To achieve the FIRST science three technologies are being pursued that will be incorporated into a single, functioning sensor: a high throughput Fourier Transform Spectrometer; a broad bandpass beamsplitter; high sensitivity detectors with a thermal design suitable for space applications. The

demonstration of the FIRST technologies will occur by deploying the FIRST instrument on a high-altitude balloon platform in the year 2005.

Shown in the figure below is a block diagram of the FIRST instrument payload as now being developed for flight on a balloon in 2005. The payload is about 36 inches tall and approximately 24 inches in diameter. There is also an additional electronics control enclosure that contains the flight electronics for FIRST. FIRST is designed to operate in either a downward looking (Earth looking) mode or an upward viewing mode. The view direction is chosen by a scene-select mirror.

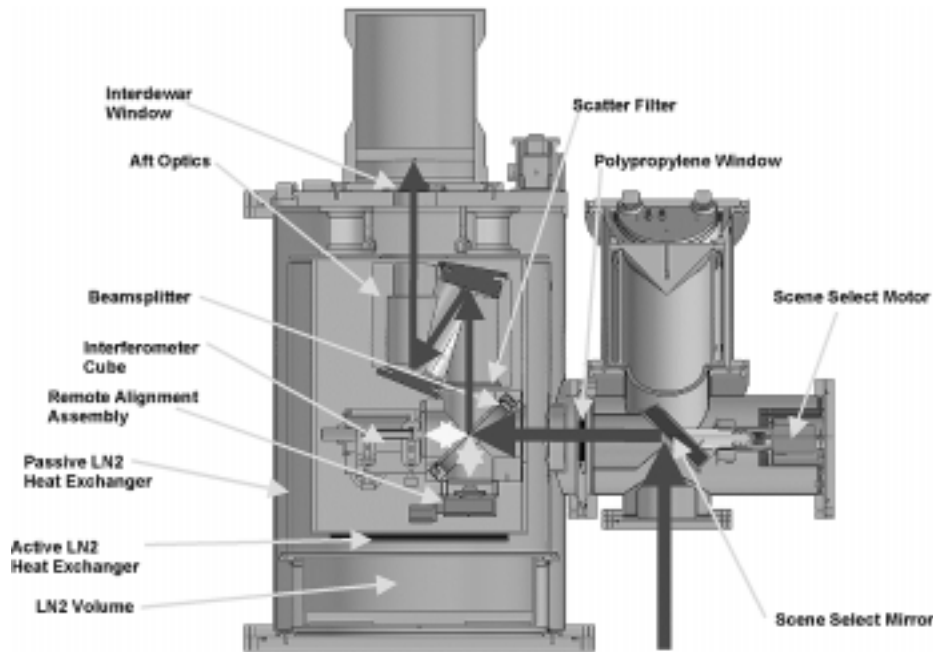


Fig. 1: FIRST block diagram.

FIRST ON SOFIA

Flying FIRST on SOFIA offers a unique potential for scientific discovery by providing unprecedented views of the far-IR spectrum of the Earth's atmosphere. In the figures below, we show examples of FIRST spectra as could be obtained from SOFIA in an uplooking mode from various flight altitudes. These simulations show both the computed spectra and the noise level for a noise equivalent temperature of 0.5 Kelvin, the FIRST design requirement, in the red line. This is the noise level for a single spectrum, which is recorded in approximately 1.2 seconds. Also shown in each figure is the expected noise level for the average of 100 spectra (pink line). Note that 100 spectra are taken in about 120 seconds, or two minutes, in which time the SOFIA would fly approximately 16 miles, which is comparable to the fields of view of the CERES and AIRS instruments presently in orbit. As is evident, the FIRST on SOFIA offers the opportunity to measure the downwelling far-IR spectrum throughout the middle and upper troposphere, into the vicinity of or above the tropopause, depending on latitude. These data would serve as fundamental validation spectra for models of water vapor, the natural greenhouse effect, cirrus radiative forcing, and temperature-water vapor feedbacks.

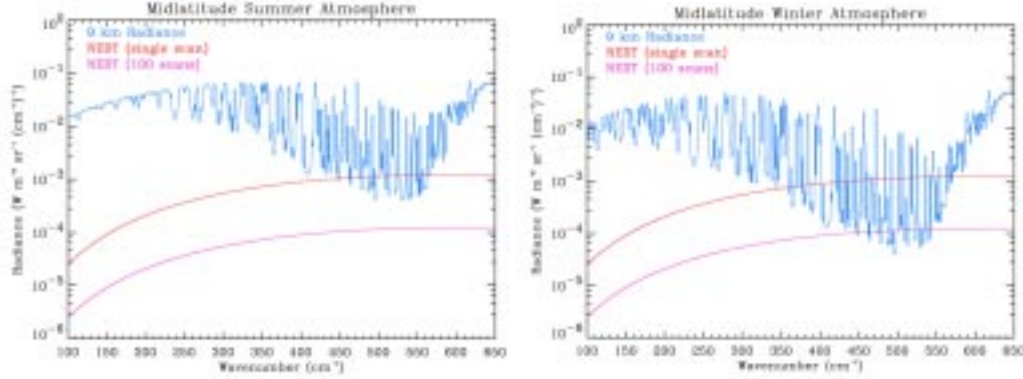


Fig. 2: FIRST zenith spectra at 9 km for mid-latitude summer and mid-latitude winter conditions.

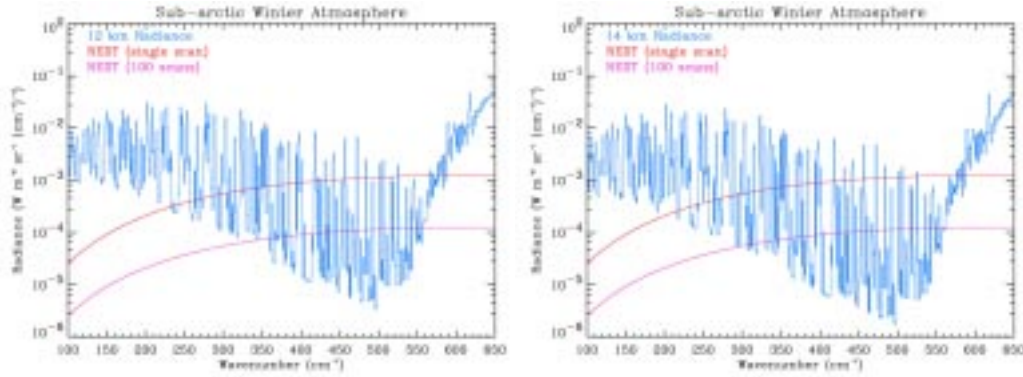


Fig. 3: FIRST zenith spectra for sub-arctic winter conditions at 12 km and 14 km flight altitudes. .

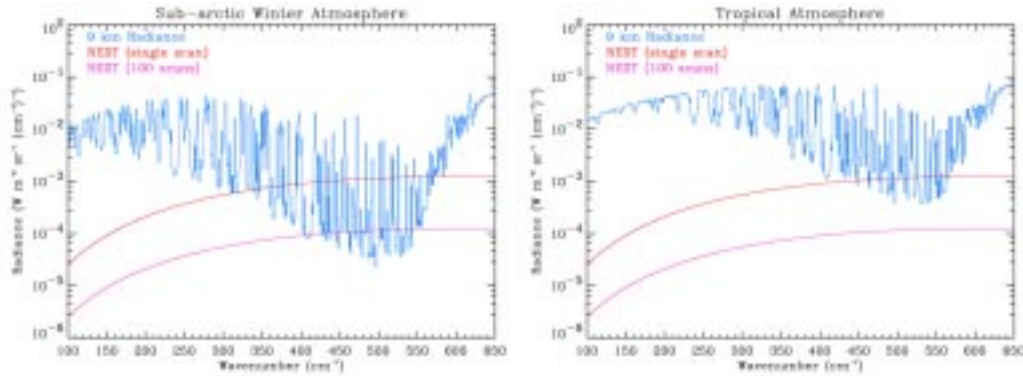


Fig. 4: FIRST zenith spectra for a sub-arctic winter atmosphere and a tropical atmosphere at 9 km flight altitude.

We note that existing and future space-based infrared spectral sensors (AIRS, IASI, CrIS) have no spectral sensing capability at wavenumbers less than 650 cm^{-1} . The simulations in Figure 2 through Figure 5 indicate the potential to measure within the atmosphere the critical-but-unobserved spectra at high ($s/n > 100:1$) precision.

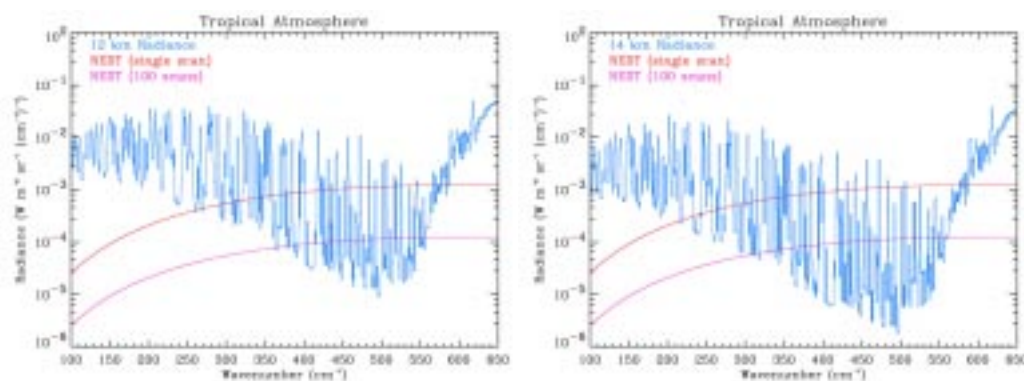


Fig. 5: FIRST zenith spectra for a tropical atmosphere at flight altitudes of 12 km and 14 km.

A notional flight plan would be to operate FIRST on SOFIA and commence science observations with the instrument in an uplooking mode through a window in the SOFIA upper deck. FIRST could start recording spectra almost immediately, and would focus on obtaining spectra between 4 km and the nominal operating altitude of the SOFIA. If possible, flight paths could coincide with satellite overflights or along predicted occultation locations of the GPS constellation so that GPS-derived temperature and water vapor could be used to simulate the FIRST/SOFIA observations, thereby providing scientific validation and confirmation of the measurements.

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